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Investigating the role of sub-auroral polarization stream electric field in coupled magnetosphere-ionosphere-thermosphere systemwide processes

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14. ABSTRACT
The proposed research is to investigate energy deposition into theionosphere (I) and thermosphere (T) system and related underlying physical processes during geomagnetic storms with the goal to improve current scientific understanding of high-latitude energetics by providing new insights. PI team has investigated a number of geomagnetic storms and magnetically disturbed time periods, and the various ionospheric plasma density features appearing such as storm enhanced density (SED), mid-latitude trough, and polar tongue of ionization (TOI).

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Investigating the role of sub-auroral polarization stream electric field in coupled magnetosphere-ionosphere-thermosphere systemwide processes

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Period of Performance: 1 June 2015 to 30 November 2016
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I.) Abstract:

This research is focused on the coupled system of Magnetosphere (M), Ionosphere (I), and Thermosphere (T). During this 18 month project, we conducted detailed studies on coupled M-I-T processes occurring during geomagnetic storms and made significant progress in the understanding of some of the underlying physical processes. Our attention was focused on M-I-T storm-time responses, how the magnetospheric input energy dissipates in the coupled I-T system, and how the sub-auroral polarization stream (SAPS) electric (**E**) field and subauroral ion drift (SAID) vary during storm times in the coupled M-I-T system. In order to further our investigations, we added thermospheric measurements to our database. Such measurements are provided by the Challenging Mini-satellite Payload (CHAMP) satellite. We developed a software package to manage and automatically handle the CHAMP data files. A procedure was also designed to present the CHAMP data in the best possible ways. Our last study is focused on investigating thermospheric responses and specifying thermospheric mass density features occurring under various magnetic conditions.

II.) Investigations carried out:

(1) Investigating how the solar wind energy becomes transferred to the coupled M-I system during the 1-2 October 2001 geomagnetic storm events (J. Geophys. Res. Space Physics, 121, doi:10.1002/2015JA022283):

Introduction:

More recently Huang et al. [2014a; 2014b] investigated energy transfer from the magnetosphere to the coupled I-T system during geomagnetic storms by utilizing Poynting flux measurements. According to their northern-hemisphere results, Poynting flux enhancements at polar and auroral latitudes were similar. Furthermore, the primary location of thermospheric heating by Joule heat was located at ~83^{o}N (magnetic) latitude in the central polar cap. These new results of Huang et al. [2014a; 2014b] demonstrate that the polar cap plays a key role in various M-I-T coupling processes, particularly during magnetic storms.

Huang, Y., C. Y. Huang, Y.-J. Su, Y. Deng, and X. Fang (2014a), Ionization due to electron and proton precipitation during the August 2011 storm, *J. Geophys. Res. Space Physics*, 119, 3106–3116, doi:10.1002/2013JA019671.
Huang, C. Y., Y.-J. Su, E. K. Sutton, D. R. Weimer, and R. L. Davidson (2014b), Energy coupling during the August 2011 magnetic storm, *J. Geophys. Res. Space Physics*, 119, 1219–1232, doi:10.1002/2013JA019297.

Results and Conclusions:

In our study we focused on the structure created by the storm enhanced density (SED) and polar tongue of ionization (TOI) over North America during the 1-2 October 2001 geomagnetic storm events. Our northern-hemisphere observational results demonstrate that 1) Joule heating intensifications occurred under southward $\mathbf{B}_Z$ conditions during active dayside merging in the central polar cap, close to the magnetic pole, 2) these Joule heating intensifications became significantly intensified in the polar TOI region (see Figure 1shown below) possibly due to the

polar TOI related high convection **E** field and large ionospheric conductivity, 3) these Joule heating intensifications minimised in the absence of polar TOI (see Figure 1), and 4) the polar TOI was present (absent) during intensive (weak) dayside merging. From our results we concluded that energy deposition occurred at multiple points and the magnetic North Pole appeared to be one of the preferred places. In the central polar cap, Q_{Joule} and ion temperature (Ti) intensified significantly (or moderately) in the presence (or absence) of polar TOI. Thus, the efficiency of input energy (EI_{eff}) could be used as a diagnostic of the intensity of polar TOI, and the thermosphere might be intensively (or moderately) impacted during dayside merging when the polar TOI is present (or absent).

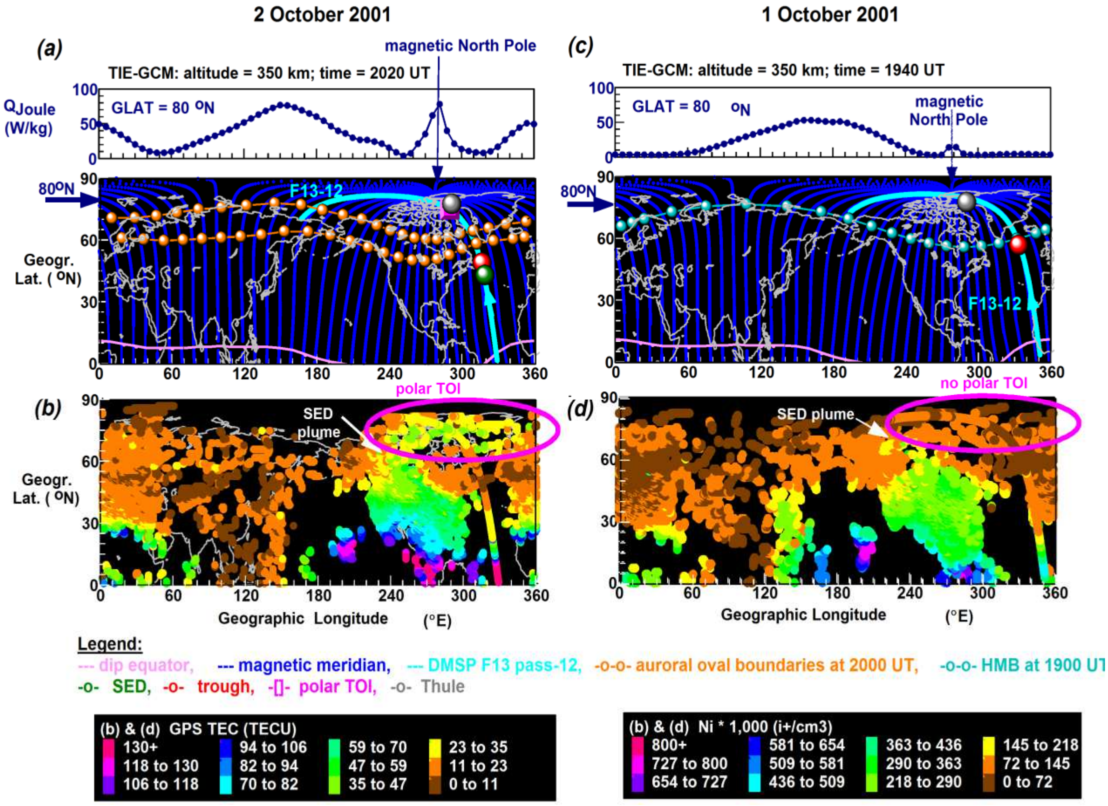

Figure 1: (a) and (c) The Q_{Joule} line plot show the variation of Joule heating at 80°N (geographic) latitude in the presence and absence of polar tongue of ionization (TOI). Enhanced (or minimal) Joule heating in the region of magnetic pole is apparent when the polar TOI was present (or absent). (b) and (d) Each northern hemisphere map shows the modelled magnetic field lines, the auroral oval boundaries or equatorward oval boundary, and the ground track of DMSP F13 pass crossing the magnetic North Pole. The GPS TEC map detected the polar TOI on 2 October 2001 and minimum polar TEC values (i.e. absence of polar TOI) on 1 October 2001.

(2) Investigating the coupling of dayside and nightside magnetic local time (MLT) sectors across the polar cap by flow channels (FCs) (J. Geophys. Res. Space Physics, 121, doi:10.1002/2016JA023109):

Introduction:

Recent studies [Nishimura et al., 2014; Lyons et al., 2015] show that nightside auroral oval intensifications are triggered by flow channels (FCs) from deep in the polar cap and occur at the contact longitude. These findings suggest 1) a significant energy input to the nightside auroral zone by FCs, 2) the coupling of dayside and nightside MLT sectors across the polar cap by FCs, and 3) some flow bursts that might originate from localized dayside reconnection and propagate across the polar cap where they trigger localized nightside reconnection and flow burst within the plasma sheet.

Lyons, L. R., et al. (2015), Azimuthal flow bursts in the inner plasma sheet and possible connection with SAPS and plasma sheet earthward flow bursts, J. Geophys. Res. Space Physics, 120, 5009–5021,doi:10.1002/2015JA021023.

Nishimura, Y., et al. (2014), Day-night coupling by a localized flow channel visualized by polar cap patch propagation, Geophys. Res. Lett., 41, 3701–3709, doi:10.1002/2014GL060301.

Results and Conclusions:

Although these above mentioned studies provide very detailed investigations of FCs, the variation of ion temperature (Ti) and upward drift (V_Z) in FCs and during dayside-nightside coupling has not yet been investigated. Our main aim in this study was to investigate FCs occurring at sub-auroral, auroral, and polar latitudes on 1 October 2001 during the recovery phase of the 30 September - 1 October 2001 medium geomagnetic storm. We focused on the southern hemisphere because of the good sets of observational results provided by the various DMSP spacecraft. As shown in Figure 2 below, our results demonstrate 1) the occurrence of a FC-2 type flow channel in the central polar cap (indicated as shaded interval in yellow), 2) the propagation of localized FC (indicated as shaded interval in blue) from the dayside to the nightside across the polar cap implying dayside–nightside coupling across the polar cap, and 3) the local intensifications of Ti and V_Z in the various types of FCs tracked. From these results we concluded that the important phenomena occurring in the polar cap during the time period invested were the 1) elevated Ti in various FCs, 2) increased upward drift (V_Z) in various FCs, and 3) dayside–nightside coupling across the polar cap and its impact on the nightside sub-auroral region.

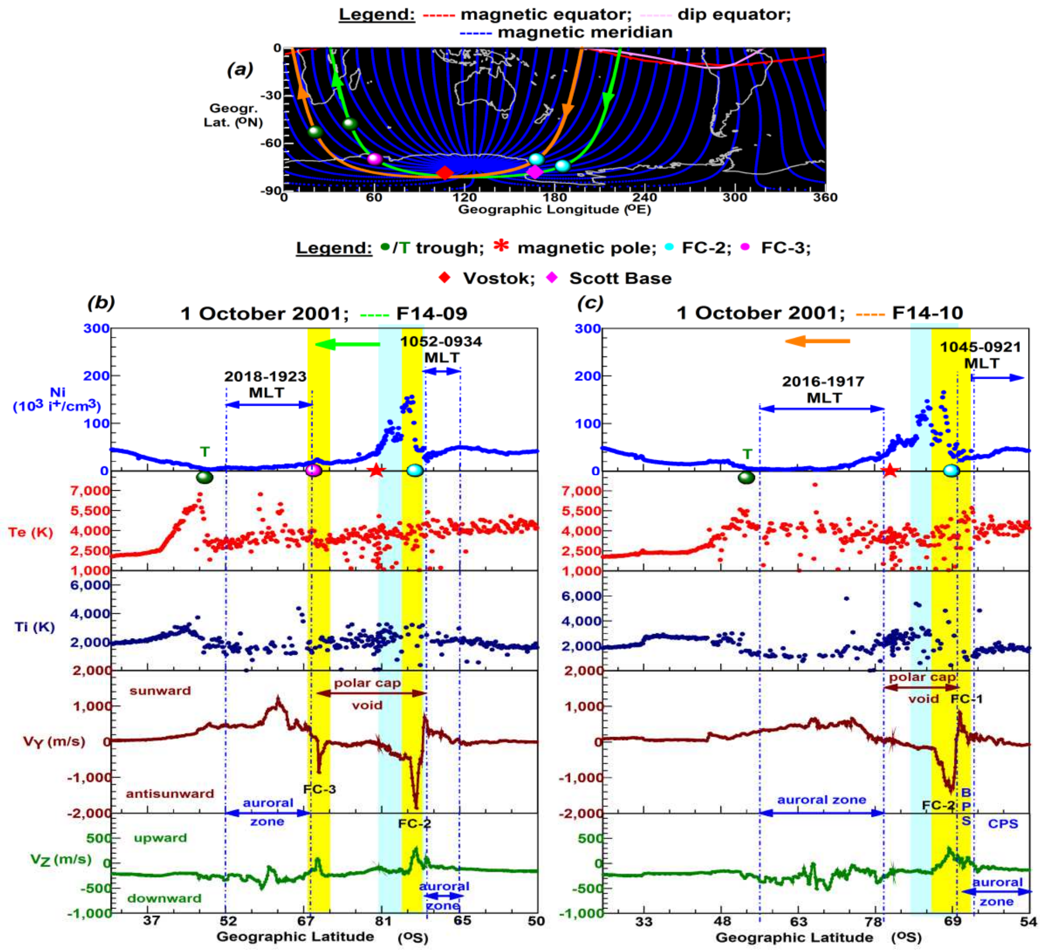

Figure 2: [a] The southern hemisphere map shows the ground tracks of DMSP passes F14-09 and F14-10 utilized, central polar cap magnetometer stations at Vostok and Scott Base, and the locations of various FCs and trough detected. [b]-[c] The DMSP line plot series depict the polar region during the various FC events occurring. FCs tracked by the V_Y line plots are marked as shaded intervals in yellow and blue.

(3) Investigating structured subauroral polarization streams (SAPS) and related auroral undulations (J. Geophys. Res. Space Physics, 121, doi:10.1002/2015JA022057):

Introduction:

Recent studies, based on satellite and radar observations, show that both the subauroral polarization streams (SAPS) and the trough can be quite irregular, displaying structures [e.g. Mishin et al., 2003, 2004]. Their resultant features are specified as SAPS wave structures (SAPS-WS) [Mishin et al., 2003] and irregular troughs [Mishin et al., 2004]. An irregular trough can be characterized by an equatorward part marked by enhanced electron temperatures and by a poleward part coinciding with strong SAPS-WS, ring current precipitations, and strong vertical ion flows [Mishin et al., 2004].

Mishin, E. V., W. J. Burke, C. Y. Huang, and F. J. Rich (2003), Electromagnetic wave structures within subauroral polarization streams, J. Geophys. Res., 108(A8), 1309, doi:10.1029/2002JA009793.

Mishin, E., W. Burke, and A. Viggiano (2004), Stormtime subauroral density troughs: Ion-molecule kinetics effects, J. Geophys. Res., 109, A10301, doi:10.1029/2004JA010438.

Results and Conclusions:

Our main aim was to investigate how the development of mid-latitude trough and auroral zone became impacted by the simultaneously occurring SAPS-WS. Our results show that 1) SAPS-WS significantly enhanced and structured the trough's poleward edge, 2) SAPS-WS impacted more intensively the stagnation trough than the trough created by chemical recombination only, 3) SAPS-related sunward drift was stronger in the deeper stagnation trough due to the feedback mechanisms, and 4) SAPS-WS developed as a response to auroral processes. We also highlighted an interesting scenario (see Figure 3 below) demonstrating that the entire trough became embedded in the SAPS-WS wherein the sunward drift (V_Y) reached 2,000 m/s.

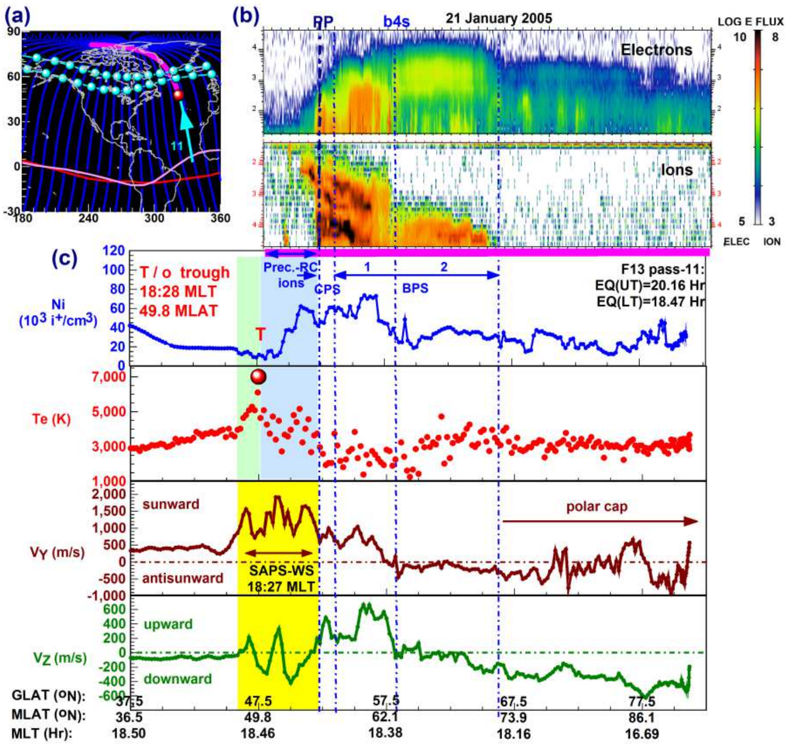

Figure 3: [a] The map shows the DMSP spacecraft's ground track passing over the magnetic North Pole. The section illustrated with spectrograms is highlighted in pink. [b] The ion and electron spectrograms tracked the signatures of precipitating ring current ions (abbreviated as Prec.-RC ions), CPS, and BPS with its structured and unstructured region-1 and -2 respectively. [c] The line plots illustrate the structured equatorward (indicated as shaded interval in light green) and poleward (indicated as shaded interval in light blue) trough regions and the underlying SAPS-WS (indicated as shaded interval in yellow).

Based on the analysis of the four SAPS-WS events presented in this study, our new findings were as follows. 1) The stagnation trough promoted stronger SAPS **E** field development and enhanced the impact of SAPS-WS on the trough itself. 2) SAPS-WS impacted not only the entire trough bottom but the trough's solar produced poleward region as well, and thus produced not only steep plasma density gradients but increased plasma densities as well. 3) The undulating sunward

auroral drifts both in the structured auroral zone and in the unstructured auroral zone led to SAPS-WS development demonstrating a strong driver-response relationship.

(4) Investigating the development of double-peak subauroral ion drift (DSAID) (J. Geophys. Res. Space Physics, doi:2016JA023506; accepted with minor corrections):

Introduction:

The double-peak subauroral ion drift (DSAID) [He et al., 2016] is a newly described phenomenon. DSAID can be regarded as a subclass of the SAID events and appears as a narrow (4^o-5^o in MLAT) double-peak feature in the sunward drift and develops during magnetically more disturbed times such as during the substorm recovery phase compared to SAID [He et al., 2016]. DSAID evolves during a two-stage process. As one of our scenarios demonstrates (see Figure 4 below) during stage-1, representing the initiation of DSAID [He et al., 2016], a strong SAID appears in the pre-midnight MLT sector that later on, during stage-2, turns into a well-developed and often symmetric DSAID (>1,000 m/s). As the DSAID progression process continues after stage-2, DSAID fades away or its two peaks merge into a single peak that finally disappears.

He, F., X.-X. Zhang, W. Wang, and B. Chen (2016), Double-peak subauroral ion drifts (DSAIDs), Geophys. Res. Lett., 43, 5554–5562, doi:10.1002/2016GL069133.

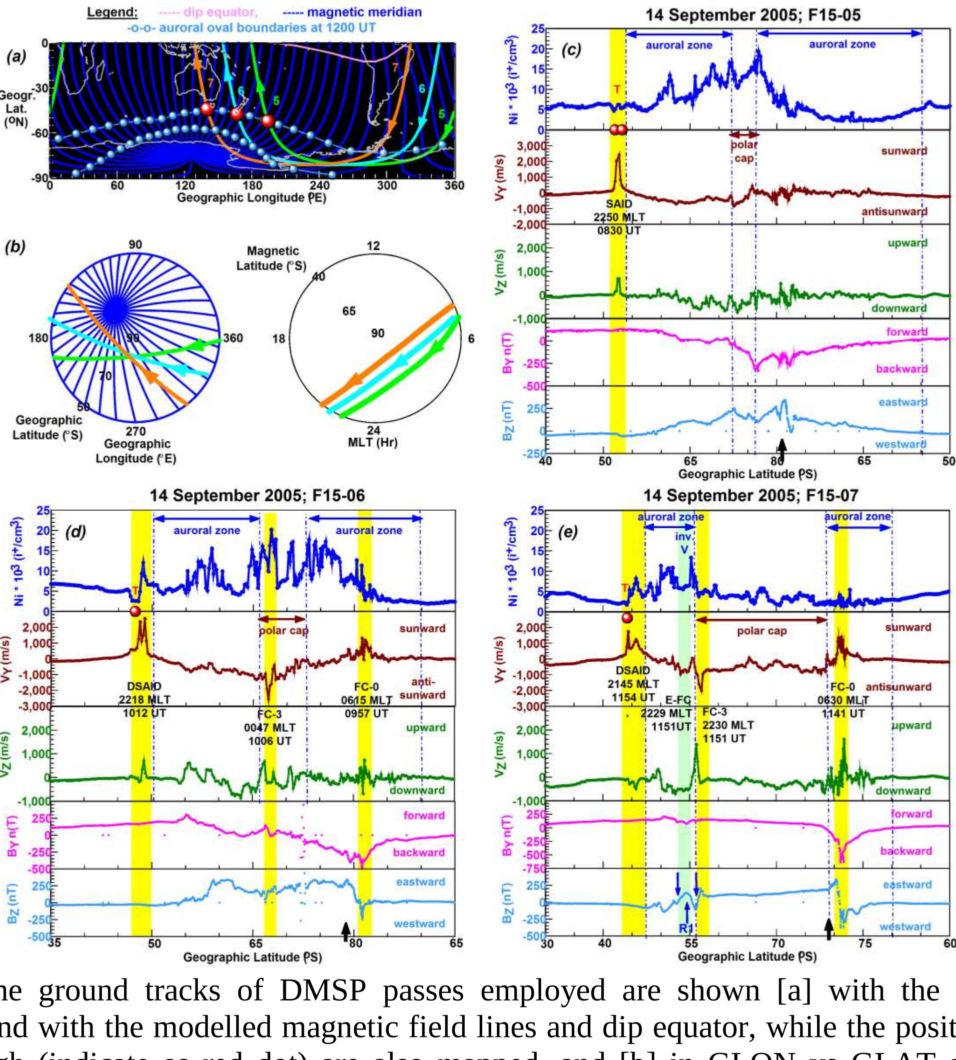

Figure 4: The ground tracks of DMSP passes employed are shown [a] with the auroral oval boundaries and with the modelled magnetic field lines and dip equator, while the positions of mid-latitude trough (indicate as red dot) are also mapped, and [b] in GLON vs GLAT and MLT vs MLAT polar maps. The line plot sets of Ni ($10^3 \times i^+/cm^3$), V_Y (m/s) and V_Z (m/s), and B_Y (nT) and B_Z (nT) illustrate polar cross sections depicting the mid-latitude trough (indicated as T and red dot) and the evolution of DSAID during scenario-4 on 14 September 2005. Shaded intervals mark the various features of interest. The blue vertical arrows indicate R1 FACs and related return currents. The black vertical arrow marks the latitude of spacecraft turning.

Results and Conclusions:

Our main aim was to investigate five DSAID scenarios in detail in order to explore the state of the polar region, to identify the accompanying FC types and their possible roles in DSAID development, and to specify the behavior of the short-circuited systems underlying DSAID. According to our findings, these five scenarios reveal that DSAID development occurred during flux transfer events (FTEs) and in a short-circuited system acting sometimes as a current generator and sometimes as a voltage generator, and was associated with various types of FCs appearing in the auroral zone (Eastward-FC, FC-0, FC-4) and polar cap region (FC-2, FC-3). While FC-2 was associated with dayside magnetopause reconnection, FC-3 was related to nightside magnetotail reconnections. From these findings we concluded that, in agreement with current studies and theories, DSAID can also be regarded as a turbulent plasmaspheric layer formed by the short-circuiting of the substorm injected hot plasma (or plasmoid) over the plasmasphere. As shown by the various scenarios, this short-circuited system acted sometimes as a current generator and sometimes as a voltage generator.

(5) Investigating the polar ionosphere during the development of neutral density enhancements on 24-25 September 2000 (J. Geophys. Res. Space Physics, doi:2016JA023799, under review):

Introduction:

Coupled M-I processes impact thermospheric dynamics and produce large variabilities in thermospheric temperature, neutral density, and neutral winds. With the launch of CHAMP satellite on 15 July 2000, providing continuous and high-resolution accelerometer and magnetometer measurements globally, thermospheric responses and their possible M-I drivers could be studied in such details that had not been possible before. First CHAMP observations of Lühr et al. [2004] documents the detection of some significant localized neutral density enhancements, appearing as spikes and reaching twice of the surrounding values. CHAMP tracked these enhancements under moderately disturbed magnetic conditions in the region of the dayside cusp where magnetospheric plasma has direct access to the lower altitude ionosphere. The simultaneously measured underlying Hall currents and small-scale (SS) field aligned currents (FACs) also showed local enhancements. This led to the conjecture that local E-region Joule heating, fuelled by SS-FACs, could be the ionospheric driver of density spikes by heating the neutral atmosphere at a lower altitudes and thus producing neutral air upwelling in the cusp region [Lühr et al., 2004]. But there is no detailed event study carried out on the solar wind (SW) and IMF conditions of 25 September 2000, providing the first CHAMP observations, and on the state of the polar region during that time.

Lühr, H., M. Rother, W. Köhler, P. Ritter, and L. Grunwaldt (2004), Thermospheric up-welling in the cusp region: Evidence from CHAMP observations, Geophys. Res. Lett., 31, L06805, doi:10.1029/2003GL019314.

Results and Conclusions:

Our main goal was to fill the above described gap in the literature by investigating the coupled SW-M-I-T processes occurring on the days of 24-25 September 2000 and the state of the polar cap region in the context of the polar convection cycle. Our results show that 1) a weak magnetic storm (SYM-H_{Min}≈-27 nT) had been unfolding on 25 September 2000 that started on the previous day, 24 September, 2) some significant flux transfer events (FTEs) occurred on these two days while the magnetic storm evolved, 3) the CHAMP detected northern density spikes on 25 September occurred in or near FC-2 type flow channels (see Figure 5 below), 4) CHAMP detected similar density spikes on the previous day, 24 September, in the southern polar region and a broader neutral density enhancement in the northern polar region. From our results we conclude that all the spikes investigated occurred during FTEs and direct SW-M-I-T coupling played a crucial role in the development of the various underlying current systems. These include the inward C2-Pedersen (C1-Pedersen) current system in FC-2 underlying the density spike in the north (south), the inward

L2-Pedersen current system in FC-4 underlying a smaller neutral density enhancement in the north, and the SS FACs embedded in the morning C1-C2 and evening L1-L2 FAC systems.

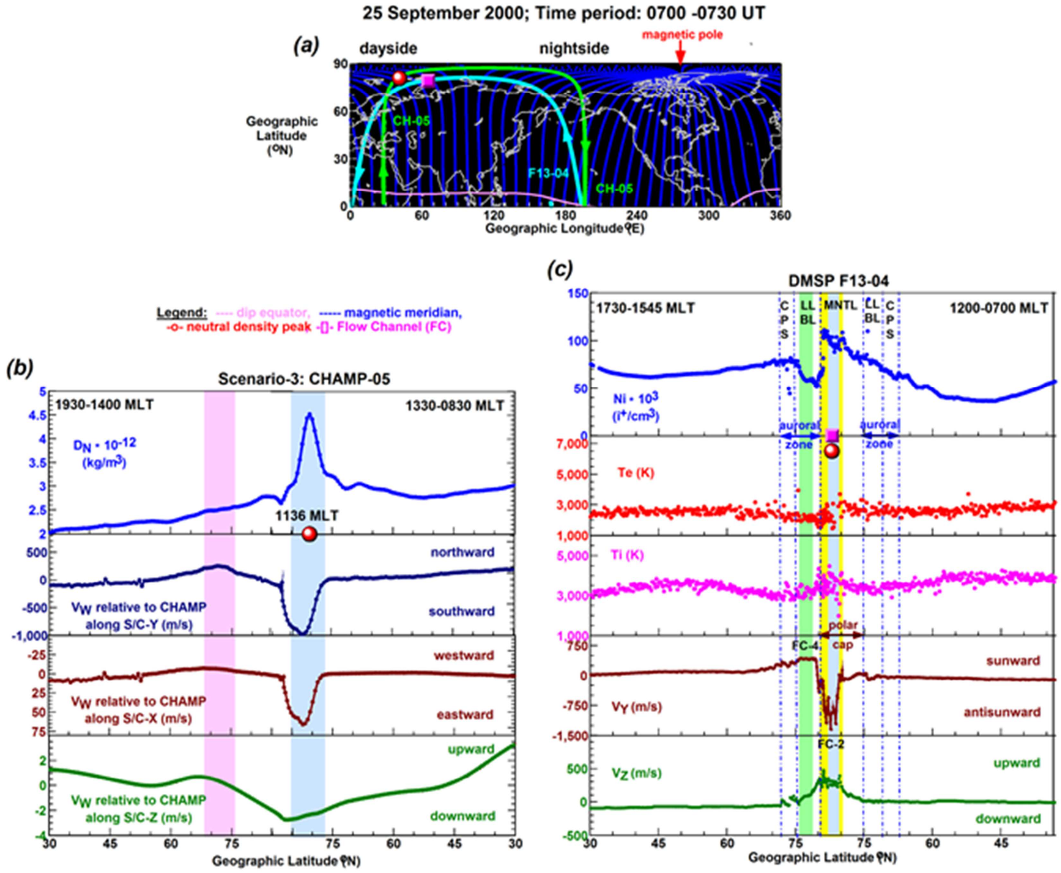

Figure 5: [a] The northern map illustrates the ground tracks of DMSP and CHAMP passes and the locations of features of interest. [b]-[c] The multi-instrument line plot series show the neutral density spike (indicated as shaded interval in light blue) with underlying winds detected by CHAMP and the state of the polar cap characterized by a FC-2 type flow channel (indicated as shaded interval in yellow) and detected by DMSP. FC-4 is indicated by the shaded interval in light magenta. The projected neutral density spike position, indicated by the shaded interval in light blue and situated close to FC-2, is also shown in the DMSP line plot series.

III.) List of publications funded by AOARD Grant FA2386-15-1-4043:

a) Papers published in peer-reviewed journals:

1. **Journal Name: J. Geophys. Res. Space Physics, 121, doi:10.1002/2015JA022057.**
   Title: Structured subauroral polarization streams and related auroral undulations occurring on the storm day of 21January 2005.
   Date of online publication: 3 FEB 2016
   Authors: Horvath, I., and B. C. Lovell

2. **Journal Name: J. Geophys. Res. Space Physics, 121, doi:10.1002/2015JA022283.**
   Title: Polar tongue of ionization (TOI) and associated Joule heating intensification investigated during themagnetically disturbed period of 1–2 October 2001.
   Date of online publication: 8 JUN 2016
   Authors: Horvath, I., and B. C. Lovell

3. **Journal Name: J. Geophys. Res. Space Physics, doi: 2016JA023506.**
   Title: Investigating the development of double-peak subauroral ion drift (DSAID).
   Date of online publication: 12 AUG 2016
   Authors: Horvath, I., and B. C. Lovell

b) Papers published in peer-reviewed conference proceedings:
None

c) Papers published in non-peer-reviewed journals and conference proceedings:
None

d) Conference presentations without papers:
None

e) Manuscripts submitted to peer-reviewed journals but not yet published:

1. **Journal Name:** J. Geophys. Res. Space Physics, doi:2016JA023506.
   Title: Investigating the development of double-peak subauroral ion drift (DSAID).
   Date received: 23 September 2016
   Authors: Horvath, I., and B. C. Lovell

2. **Journal Name:** J. Geophys. Res. Space Physics, 121, doi:2016JA023799.
   Title: Investigating the polar ionosphere during the development of neutral density enhancements on 24-25 September 2000.
   Date received: 14 December 2016
   Authors: Horvath, I., and B. C. Lovell

f) List any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

IV). Seminars presented

1. **Even Name:** Visit of Dr Brian Lutz, AOARD/AFOSR Science Program Manager, to UQ, Brisbane, Australia
   Title: Investigating Coupled Magnetosphere-Ionosphere Processes
   Date: 28 October 2015
   Presenter: Dr Ildiko Horvath

2. **Even Name:** Visit of Dr Tim Lawrence, Head of AFOSR International, to UNSW, Sydney, Australia
   Title: Investigating Space Weather
   Date: 22 February 2016
   Presenter: Prof Brian Lovell

3. **Even Name:** 2016 Joint CEDAR-GEM Workshop, Eldorado Hotel and Santa Fe Convention Center, Santa Fe, NM, USA
   Title: Flow channel events during the 31 August 2005 geomagnetic storm
   Date: 19-24 June 2016
   Presenter: Dr Cheryl Huang, Senior Research Physicist, AFRL/RVBXP, Kirtland AFB, NM, USA

V). Award for best paper, poster:
None

VI.) Award of fund received related to your research efforts:
None

VII). Attachments: Publications a)